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Hydrologic Aspects of Water Sustainability and Their Relation to a National Assessment of Water Availability and Use

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While requirements to leave water in streams and rivers for environmental and recreational uses are expanding, competition for water to meet the needs of homes, cities, farms, and industries is also increasing. As a result, many citizens are asking "Are we running out of freshwater?" In response to an expressed concern by the U.S. Congress about the future of water availability for the Nation, the U.S. Geological Survey (USGS) was directed to prepare a report describing the scope and magnitude of the efforts needed to provide periodic assessments of the status and trends in the availability and use of the nation's freshwater resources (U.S. Geological Survey 2002). As envisioned by the USGS, the periodic assessments would consist of two primary components: (1) the development and reporting of up-to-date, nationally consistent indicators of the status and trends in surface-water flows and storage, ground-water storage and depletion, and water withdrawals and uses nationwide; and (2) improved estimates of regional-scale water budgets and water-cycle components (streamflow, evapotranspiration, interbasin transfers, and so forth) across the country.

The proposed national assessment is intended to provide the nation with an overview of the status and future of its water resources. The overarching question to be answered by the program is "What is the availability of water resources in the nation and how does this availability relate to demand, source, and geographic location?" Water availability and use depend on a number of factors that affect both the natural (or raw) resource and the developed resource (that part of the natural resource that is reliably available for use). These factors include: the total flow and quality of water within a basin; water-supply demands; and the structures, laws, regulations, and economic factors that control water use (fig. 1). Therefore, to develop a complete picture of the nation's freshwater availability and use, the hydrologic information produced through the proposed assessment would need to be aggregated with other types of physical, social, economic, and environmental data illustrated in figure 1. Clearly, water availability and use are closely related to the concept of water sustainability, which can be thought of as an approach for managing water resources. For the purposes of this paper, we define water-resources sustainability in a broad context as the development and use of water resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

The building blocks of the proposed assessment are fundamental measurements and scientific analyses of the basic components of the natural and developed resource—that is, quantification of the nation's water capital throughout the natural and developed components of the hydrologic cycle. High-quality hydrologic data and sound hydrologic analyses are essential to understanding the availability, use, and sustainability of U.S. freshwater resources. In the remainder of the paper, we first discuss some of the important hydrologic aspects of water-resources

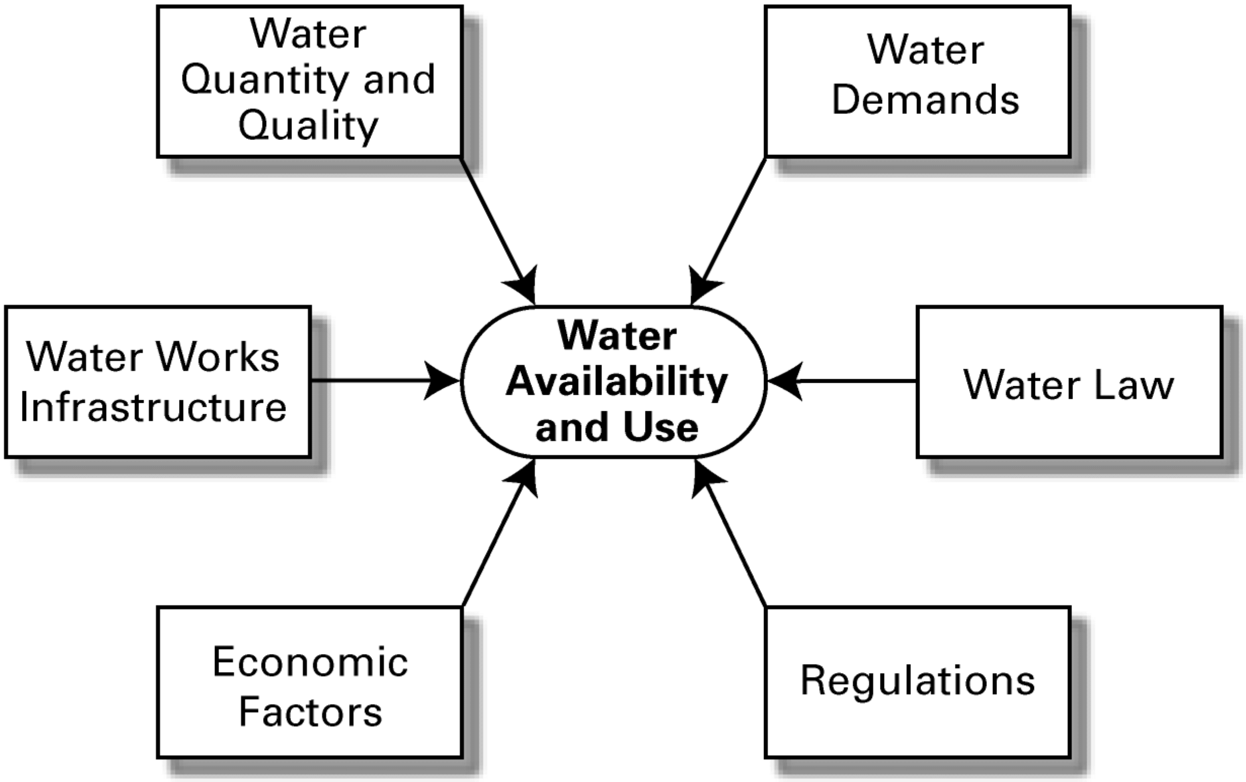


Figure 1. Water availability and use depend on a number of factors that affect both natural and developed water resources.

sustainability that also underlie the plan for a national assessment of water availability and use; then we describe some of the design concepts of the two components of the proposed national assessment.

Hydrologic Aspects of Water Sustainability

Key hydrologic aspects of water-resources sustainability that are relevant to the design of a national assessment of water availability and use include the dynamic nature of water-resource systems, the need to consider the complete hydrologic system, the importance of a long-term perspective toward management of water resources, and the dependence of sustainability analysis on spatial scale (Alley 2002). These are described briefly below.

Water resources cannot be developed without altering the natural environment, yet the effects of water-resources development may require many years to become evident. As an example, consider a well that pumps ground water from an aquifer that is in hydraulic connection with a stream (fig. 2). The surface-water source in this example is a stream, but it could be another surface-water body such as a lake or wetland. At the start of pumping, all of the water supplied to the well comes from ground-water storage. Over time, the dominant source of water to a well, particularly wells that are completed in unconfined aquifers, commonly changes from ground-water storage to surface water (fig. 3). The source of water to the well from the stream can be either decreased ground-water discharge to the stream or increased flow (recharge) from the stream to the ground-water system. In either case, the net result is decreased flow in the stream (streamflow capture). In the long term, the cumulative streamflow capture for many ground-water systems can approach the quantity of water pumped from the ground-water system, as seen in figure 3. The time for the change from the dominance of withdrawal from ground-water storage to the dominance of streamflow capture can range from weeks to years to decades or longer, depending upon the hydraulic characteristics of the aquifer and the distance of the well from the stream. From a sustainability perspective, the key point is that pumping decisions today will affect surface-water availability; however, these effects may not be fully realized for many years (Alley and Leake 2004).

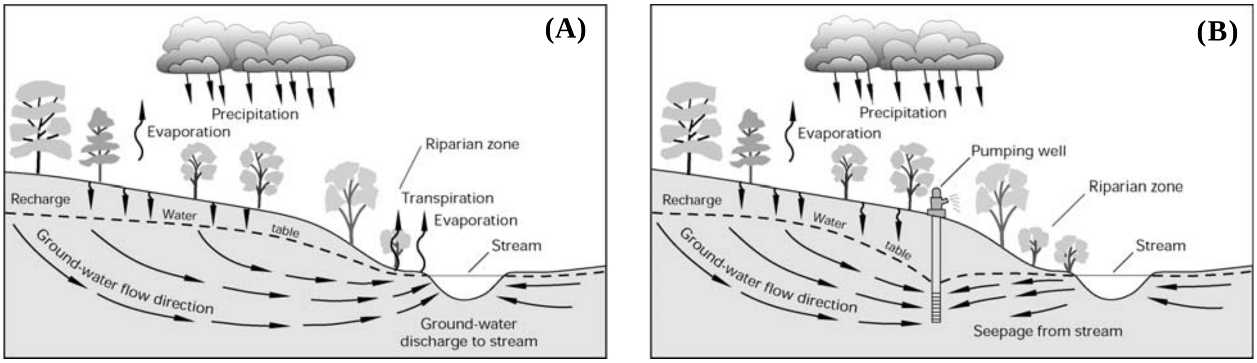


Figure 2. Ground-water flow near a stream under natural conditions (A) and with ground-water withdrawals (B).

Not only do hydrologic systems vary with time as a function of human interactions, but also in response to changing climatic and other environmental conditions; thus, even a 40- to 50-year period of streamflow record unaffected by ground-water withdrawals provides only a snapshot of a continually varying hydrologic system. Such variability may be particularly important with respect to extreme events such as droughts, and highlights the complexity of defining the sustainability of a hydrologic system.

The conditions shown in figure 2 are typical of many hydrologic systems in which the ground-water and surface-water systems comprise a single resource. Because of the interdependence of surface water and ground water, changes in any part of the system have consequences for other parts. For example, what may be established as an acceptable rate of ground-water withdrawal with respect to changes in ground-water levels may reduce the availability of surface water to an unacceptable level. The reductions in streamflow may affect not only water supply for human consumption but also the maintenance of instream-flow requirements for fish habitat and other environmental needs. Long-term reductions in streamflow can affect vegetation in the riparian zones along streams that serve critical roles in maintaining wildlife habitat and protecting the quality of surface water. Thus, the cumulative effects of pumping can produce significant and unanticipated consequences on surface-water resources.

Nationwide, the renewable supply of water (precipitation less evapotranspiration) is much larger than the rate of consumptive use. From an overall national perspective, therefore, water resources appear ample. Across the nation, however, the

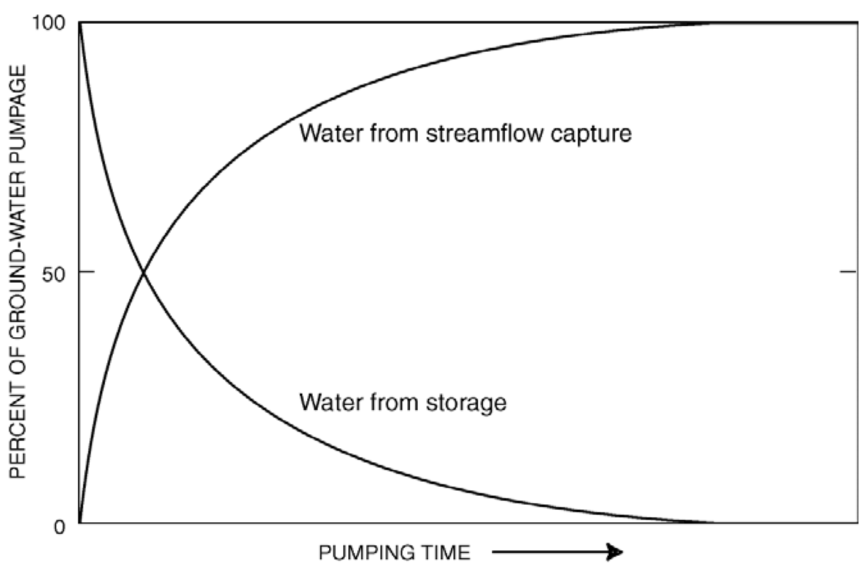


Figure 3. Sources of water to a well change with time.

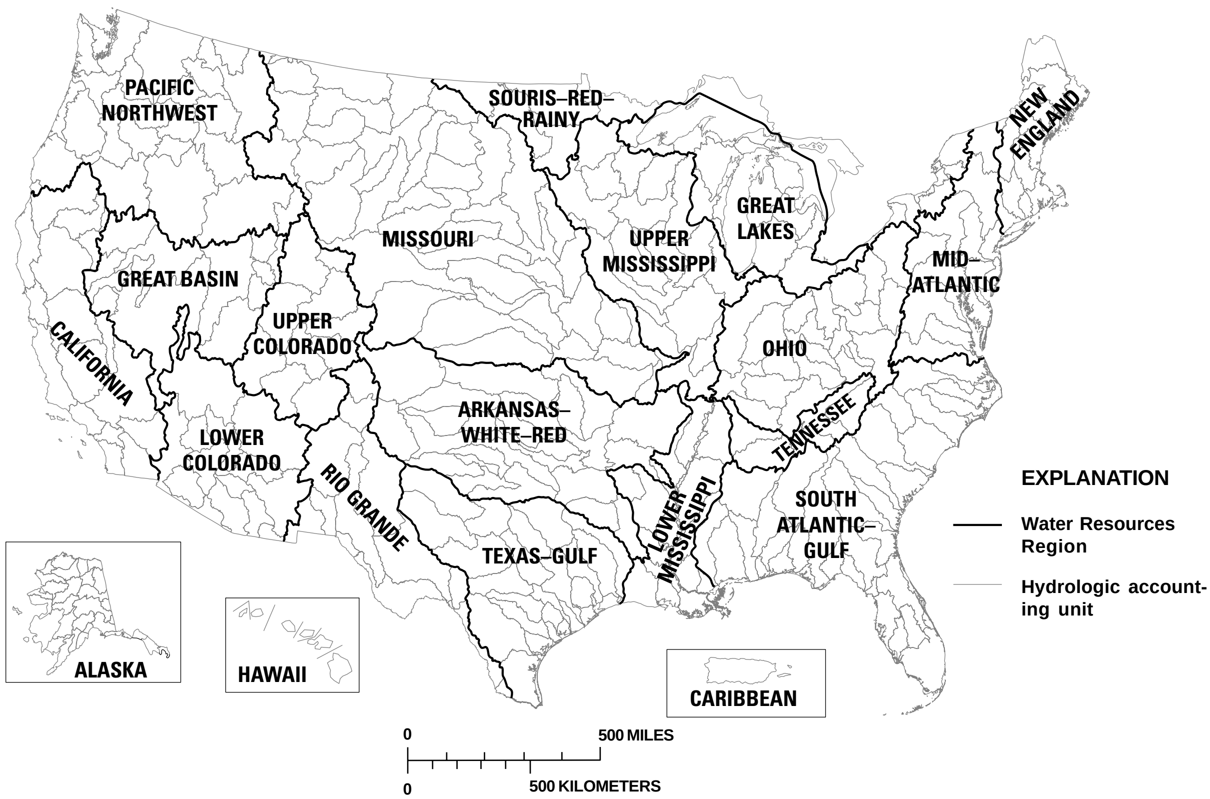


Figure 4. Water Resources Regions and hydrologic accounting units of the United States (U.S. Geological Survey, 1982).

situation varies widely, with areas of relative abundance east of the Mississippi River and in the Pacific Northwest, Alaska, Hawaii, and the Caribbean, and areas of relative scarcity (defined as regions where consumptive use is greater than 10 percent of the renewable supply) in the remaining Water Resources Regions shown in figure 4. Locally, even regions of relative abundance can have challenging water-availability and sustainability issues. This is demonstrated, for example, in parts of the northeastern United States (U.S.) where, although water is abundant, there is competition between the water-resource needs of rapidly growing communities and those of aquatic and riparian ecosystems that depend on instream flows.

Concepts for a National Assessment of Water Availability and Use

The national assessment of water availability and use proposed to Congress would be based on measurements and analyses of components of the natural and developed hydrologic systems. The primary audience for the products of the assessment would be policy makers and public officials in Federal agencies, the Congress, nongovernmental organizations with an interest in natural resources, and the general public. The assessment also would provide water-resource engineers and planners at the state and local level with uniform information about the resource that would provide a context for more detailed planning of water-related projects and water-resource allocations. The role of the federal government in the collection and sharing of water data to support state efforts in water management was recently highlighted in a report by the U.S. General Accounting Office (GAO) to members of Congress (U.S. General Accounting Office 2003). Water managers from 39 states who responded to a GAO survey on how federal actions could best help states meet their water-resource challenges indicated that expanding the number of federal data-collection points, such as streamgaging sites, was the most useful federal action to help their state meet its water-information needs.

Some of the design considerations of the two major components of the national assessment are described in the following paragraphs.

Table 1. Summary of an initial set of indicators for a national assessment of water availability and use.

Surface-water indicators

Streamflow: annual and periodic (5- to 10-year) summaries; assessments of long-term trends

Reservoir storage, construction, sedimentation, and removal

Storage in large lakes, perennial snowfields, and glaciers

Ground-water indicators

Ground-water-level indices for a range of hydrogeologic environments and land-use settings

Changes in ground-water storage due to withdrawals, saltwater intrusion, mine dewatering, and land drainage

Number and capacity of supply wells and artificial recharge facilities

Water-use indicators

Total withdrawals by source (surface water and ground water) and sector (public supply, domestic, commercial, irrigation, livestock, industrial, mining, and thermoelectric power)

Reclaimed wastewater

Conveyance losses

Consumptive uses

Indicators of Water Availability and Use

Indicators of the status and trends in storage volumes, flow rates, and water uses nationwide are not available currently in an up-to-date, nationally comprehensive and integrated form. Although it is clear that water-availability indicators should be built from basic hydrologic data, the transformation of the raw hydrologic and water-use data into a meaningful set of indicators that shed light on changing conditions of water availability, use, and sustainability, and that contribute to a more comprehensive set of environmental indicators for the nation, will require a significant development effort. Table 1 provides a summary of an initial set of surface-water, ground-water, and water-use indicators that serve as a starting point for indicator development and reporting.

Two important considerations in the design of water-availability indicators are the spatial and temporal scales at which the indicators should be reported. There are several spatial scales at which the indicators could be reported. Past assessments have focused on the individual states and the 21 major Water Resources Regions of the United States (fig. 4).Because of technological advances for managing, presenting, and sharing spatial data, it is now possible to provide information to decision-makers at a more refined scale. Initially, the proposed assessment would use the 352 river-basin hydrologic accounting units (fig. 4) as the basic reporting unit for the national indicators. These accounting units are watersheds that typically range in size from 5,000 to 20,000 square miles. In most cases, however, boundaries of the hydrologic accounting units do not coincide with those of major aquifer systems. Ground-water variables, therefore, should be reported primarily by major aquifer system.

Water availability varies seasonally and from year-to-year in response to changing weather conditions and water-use demands. A meaningful national assessment needs to remove seasonal and short-term variability to isolate trends and patterns that have regional and national significance. Currently, the USGS provides various real-time and historical streamflow products at daily to monthly time scales, such as the online *WaterWatch* internet site (http://water.usgs.gov/waterwatch/). The flow of the nation's rivers also is changing in important ways at annual to decadal time scales due to changes in land use, ground-water development, flow regulation, and climate; it is to these time scales that streamflow aspects of the proposed assessment should be directed. Changes in ground-water use and the effects of ground-water development are not as variable from year-to-year as are those for surface water. Therefore, periodic assessments of ground-water storage could be made at 5- to 10-year intervals. Water-use estimates for the nation have been compiled and disseminated by the USGS at 5-year intervals since 1950. As water-use estimation techniques improve, efforts should be made to move toward annual accounting of high-priority water-use sectors such as public supply and irrigation.

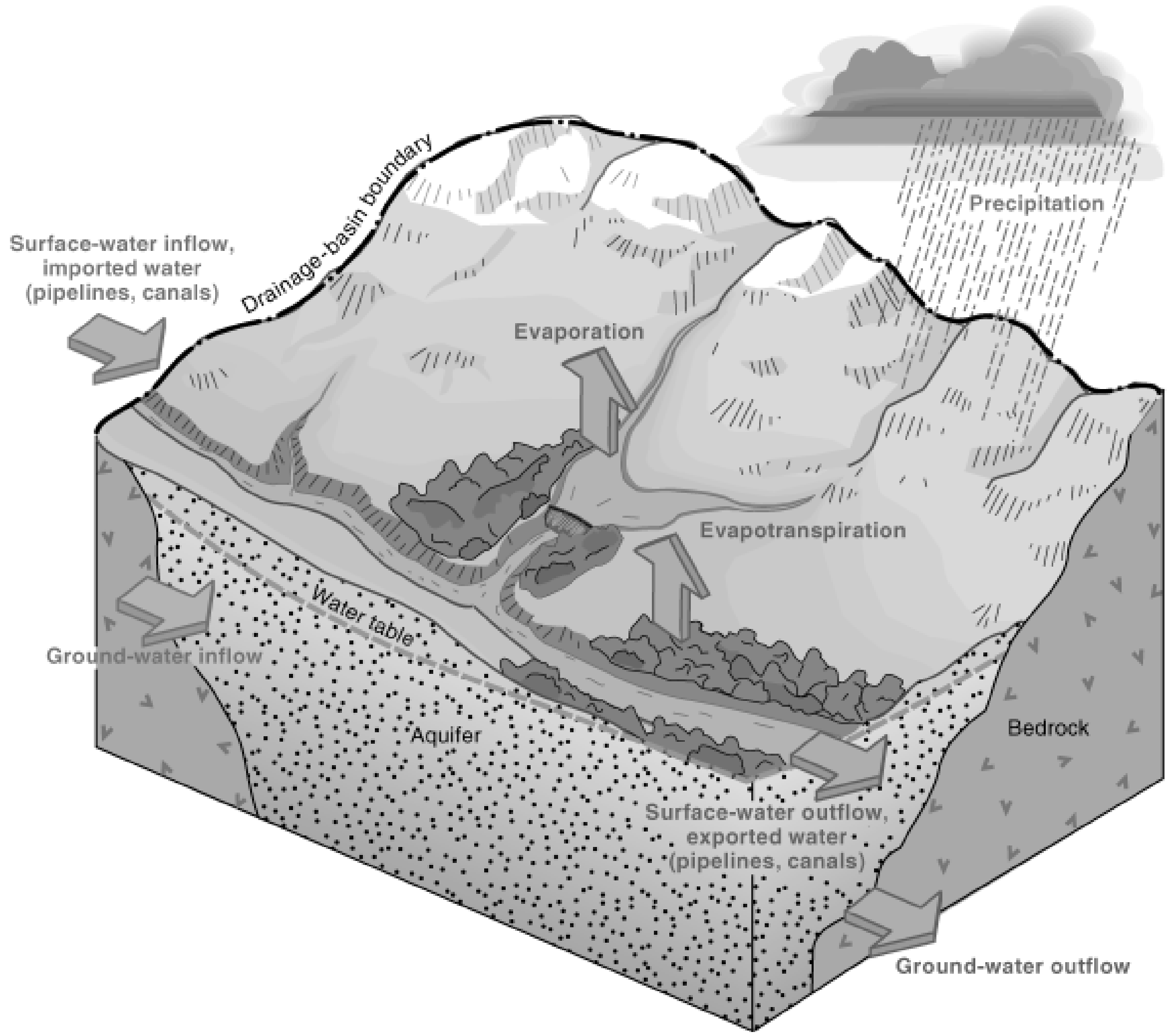
A third consideration in the development of a set of water-related indicators is the extent and quality of the water-resource data-collection networks on which the indicators (and broader assessment) would be based. The process of computing water-availability indicators from basic data would help to identify uncertainties in our knowledge of the nation's hydrologic conditions, and it would also provide useful feedback to the design and improvement of data-collection networks. Although an initial national assessment of the annual status and decadal-scale trends in surface-water discharge and storage for the 352 river-basin hydrologic accounting units could be completed within a few years, ground-water and water-use data are not as well developed. As noted by Taylor and Alley (2002), a national program to systematically monitor and assess ground-water reserves or the sustainability of ground-water pumping does not exist. Moreover, according to a recent report on *The State of the Nation's Ecosystems*, data on ground-water levels and rates of change are "not adequate for national reporting" (H. John Heinz III Center 2002). Networks of existing monitoring wells vary considerably across the country and the data are housed in many agencies. Thus, initial efforts for a national assessment would require an inventory of existing water-level networks for major aquifer systems and development of indices that can be used to track ground-water-level changes for the nation and for specific geographic regions and aquifers. Synoptic measurements of ground-water levels over broad areas would be necessary to provide estimates of ground-water depletion regionally and ultimately nationwide.

Existing water-use estimation efforts also need to be strengthened and enhanced to reflect the increased importance of, and demand for, national water-use data and analyses. In 2002, the National Research Council (NRC) reviewed the role of the USGS in providing water-use information and made a number of recommendations to develop improved water-use estimates and a national database of water-withdrawal, conveyance, consumptive-use, and return-flow information (National Research Council 2002). A key recommendation of the NRC review was to use sampling strategies and regression modeling to develop statistically derived water-use estimates. This statistical approach would identify demographic, economic, geologic, hydrologic, and climatic indicators that are correlated with water use and that can be used to supplement existing water-use data. An enhanced national water-use database should be developed and maintained to provide ready access to water-withdrawal, conveyance, consumptive-use, and return-flow information.

Regional Water Budgets

Whether or not a particular water-resource development action is sustainable depends on an accurate determination of the amounts of water entering, leaving, and stored within a particular Water Resource Region or watershed (fig. 5). Because hydrologic, climatic, demographic, and other factors that affect water availability and use vary geographically, the relative importance of individual components of the water cycle varies across the nation. As a consequence, a program for improved determination of regional water budgets needs to be tailored to the conditions that exist within the different Water Resources Regions of the United States. Historically, some water-cycle components have proven difficult to estimate accurately, such as evapotranspiration, and would require the development of new methods for their determination. Moreover, even for those water-cycle components that can be measured accurately, data often are lacking to quantify components at a particular location. Therefore, the adequacy of existing data-collection networks within each region will need to be determined, and it is anticipated that new data-collection stations will need to be established where existing data are inadequate for water-budget estimates.

The Great Lakes Basin watershed (fig. 6) provides a good example of the need for improved information on regional water budgets to inform discussions and decisions concerning water availability and sustainability, and it also demonstrates some of the challenges in the implementation of a national assessment of water availability. The governors of the eight Great Lakes states and the premiers of the Canadian provinces of Ontario and Quebec are committed to develop and implement a new common, resource-based conservation standard for water-resources management through Annex 2001 to the Great Lakes Charter of 1985 (Council of Great Lakes Governors 2001). The conservation standard will apply to new proposals for water withdrawals from the "Waters of the Great Lakes Basin," which includes tributaries to the Great Lakes, the Great Lakes proper, connecting channels between the lakes, and ground water within the Basin. The Charter Annex provisions will require that new proposals to withdraw water from the Great Lakes Basin, as well as proposals to increase existing water withdrawals or existing water-withdrawal capacity, not result in adverse effects on the "water" or "water-dependent" natural resources. The Charter Annex is part of a growing awareness that water use, withdrawals, and biodiversity are strongly connected. In fact, all three are critical to the



Simplified Water Budget

(WATER INFLOW)–(WATER OUTFLOW)=(CHANGE IN WATER STORAGE)

Typical water budget components

WATER INFLOW
—Precipitation
—Surface-water flow into basin
— Imported water
—Ground-water inflow

WATER OUTFLOW
—Evaporation
—Transpiration by vegetation (evapotranspiration)
—Surface-water outflow
—Exported water
—Ground-water outflow

CHANGE IN WATER STORAGE, increased/decreased water in:
—Snowpack
—Unsaturated soil zone
—Stream, rivers, reservoirs
—Aquifers

Figure 5. Water-cycle components and simplified water budget of a drainage basin (Figure modified from U.S. Geological Survey, 2002).

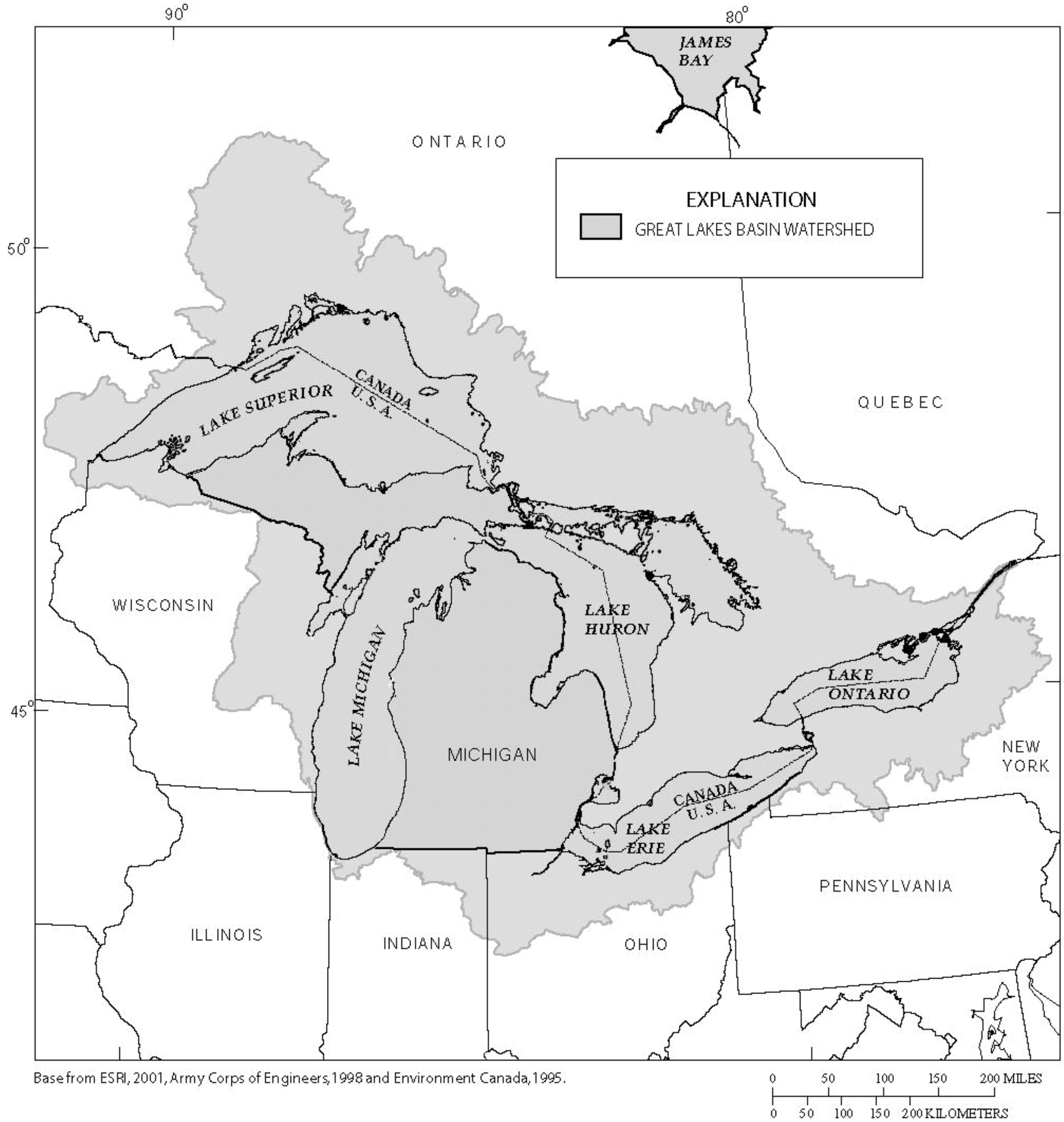


Figure 6. Location of the Great Lakes Basin.

economy and health of the surrounding human population through tourism, recreation, fisheries, and water use for human needs and ecosystem functions. Even though the resource is vast, uncertainties in the estimates of water inflows, outflows, and uses in the Great Lakes Basin threaten the ability of the states to provide defensible decision-making actions under Annex 2001 to the Great Lakes Charter.

Developing and implementing a standard for Annex 2001 requires an understanding of the impact of withdrawals on water availability for humans and ecosystems in the Great Lakes and in the Great Lakes watershed in the United States and Canada. The components of the basic water budget of the Great Lakes and their watersheds include precipitation on the lake surface, evaporation from the lake surface, streamflow into the lake, ground-water flow into and out of the lake, connecting channel inflows and outflows, withdrawals, and consumptive uses. Presently, the USGS, in collaboration with the National Oceanic and Atmospheric Administration, the U.S. Army Corps of Engineers, and the Great Lakes Commission, is assisting in a qualitative evaluation of the Great

Lakes water budget. Preliminary findings indicate that the errors and unknowns in the Great Lakes water budget are likely to be much larger in volume than current or foreseeable proposals for most water withdrawals.

For most components of the water budget, a systematic evaluation of current measurements and computations is needed to determine the most cost-effective, long-term changes that would significantly reduce errors. In particular, improvements are needed in the computations of tributary and connecting channel streamflow, ground-water contributions, and consumptive uses. Some water withdrawals may be negligible compared to the total amount of water in the Great Lakes, but these volumes may be large relative to the tributary stream from which the water is withdrawn, and a large number of small withdrawals may have the same effect as a single large withdrawal.

Currently, tributary streamflow is measured by streamgages for about 70 percent of the U.S. portion of the Great Lakes Basin, but an evaluation of the current streamgaging network is needed to determine what percentage of the Great Lakes Basin needs to be gaged for water-budget computations. Also needed is a robust method to compute the streamflow entering the Great Lakes from ungaged (unmeasured) tributary streams so the contribution from these ungaged streams to the water budget can be determined. Connecting channel flows routinely are computed for the St. Mary's, St. Clair, Detroit, and Niagara Rivers in the United States, but the techniques used to measure and compute these flows at most stations were developed some time ago. For example, the error in flow computation for the Detroit River may be as much as 18,600 cubic feet per second, which is more than five times the amount of water diverted from Lake Michigan at Chicago (the largest diversion out of the Great Lakes Basin).

Flows in many streams of the Great Lakes Basin are modified from their natural conditions by alterations to their watershed. Biota in streams are strongly affected by altered flows. As a result, an analysis of flow alterations across the Great Lakes watershed, if linked to potential biological impacts, would address key Annex questions regarding the impact of withdrawals on aquatic ecosystems and would provide needed streamflow information for drought conditions. In addition, return flows—such as those from wastewater treatment plants—alter the quality of streams, particularly during periods of low flow. A basin-wide computation of the amount of water in streams that comes from return flows will help bound the upper limit for withdrawals in many parts of the basin.

Although ground-water flow into and from the Great Lakes currently is not measured, indirect ground-water flow to the Great Lakes by way of tributary streams has been computed for the U. S. portion of the basin by the USGS, and is estimated to be a large part of the Great Lakes water budget (Grannemann et al. 2000). The amount of ground water that flows directly into the Great Lakes is unknown, but an estimate can be made by a more detailed analysis of existing information and ground-water model analysis. Ground-water divides (comparable to watershed divides for tributary streams) have not been determined for the Great Lakes Basin, but it is known that there are ground-water contributions into the Great Lakes that do not coincide with the watershed boundaries for tributary streams.

The Great Lakes Charter defines consumptive water use as "that portion of water withdrawn or withheld from the Great Lakes Basin and assumed to be lost or otherwise not returned to the Great Lakes Basin due to evaporation (during use), due to incorporation into products, or into other processes." Methods to estimate consumptive use are crude and rarely based on data specific to the Great Lakes. The major consumptive water uses in the Great Lakes are for public supply, irrigation, industry, and thermoelectric power generation. Estimates of consumptive use specific to the Great Lakes Basin and considerably more reliable than current estimates are needed for each of these categories. In addition to consumptive uses, water transfers into and out of the basin through human infrastructure also need to be systematically quantified.

The effects of water withdrawals on regional water budgets in the Great Lakes have been documented in a few places. Declines in ground-water levels near Toledo, Ohio; Chicago, Illinois; and Milwaukee, Wisconsin, and the effects of these declines on the flow of ground water provide interesting examples (Grannemann et al. 2000). Pumping the carbonate aquifer and dewatering a quarry near Toledo, Ohio, have lowered ground-water levels as much as 35 feet below the average levels of Lake Erie, and have induced water from Lake Erie into the ground-water system and intercepted water that would have discharged from the ground-water system to Lake Erie (Breen 1989; Eberts 1999). Ground-water levels in the sandstone aquifer underlying areas from Chicago, Illinois, to Milwaukee, Wisconsin, have been lowered by industrial and public withdrawals by as much as 375 feet near Milwaukee and by as much as 900 feet near Chicago (Young 1992). Although some recovery has taken place in parts of Chicago through reductions in withdrawals, lowering of the ground-water levels in the 1980's resulted in a displacement of the ground-water divide by about 50 miles to the west of its prepumping location, beyond the surface-water divide of the Great Lakes. "The hydrologic system is further complicated by the fact that most of the effluent from ground-water withdrawals in the Chicago area is discharged to the Mississippi River Basin via the Chicago Diversion—one of the few places where water is diverted from the Great Lakes Basin." (Grannemann et al. 2000).

Summary

In response to a directive from the U.S. Congress, the USGS recently prepared a plan for periodic assessments of the status and trends in the availability and use of the nation's freshwater resources. The proposed assessment would develop and report a set of nationally consistent indicators of surface-water flows and storage, ground-water storage and depletion, and freshwater withdrawals and use. The assessment also would provide improved estimates of regional-scale water budgets and water-cycle components across the nation. Fundamental to the proposed assessment are a number of important hydrologic aspects of water-resources sustainability, namely:

- Hydrologic systems are dynamic, but also often respond slowly to changes in land use, water-resources development, and climate. A national assessment would focus on long-term trends and patterns in water availability and use that have regional and national significance.
- Hydrologic systems consist of interrelated water-cycle components, and stresses to any of the individual components can propagate to the other components. Therefore, meaningful analyses of water availability and sustainability should be based on accurate knowledge of all components of the water budget of a basin or watershed. The importance of individual water-cycle components to the water budget of a particular basin varies across the nation because of geographic variability in hydrology, climate, water use, and other factors that affect water resources.
- Water availability and sustainability are a function of spatial scale. A particular water-resource development plan that appears to have little impact at the scale of a Water Resources Region or large watershed may, in fact, have large impacts on the sustainability of a particular ecosystem within the basin in which the development occurs. A national assessment of water availability and use, therefore, should provide a uniform set of information that gives a picture of the status and trends of water-resources conditions for the nation as a whole, but to the extent possible, also be disaggregated for use in detailed water-resources planning at the state and local levels.

The Great Lakes Basin provides a good example of the need for periodic reporting of the status and trends of water availability indicators and use within a watershed. It also illustrates the importance of improved estimates of selected water-cycle components to better understand the regional water budget of the watershed and the impact of withdrawals on water availability for humans and ecosystems.

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